Evaluation of a passive optical based end of service life indicator (ESLI) for organic vapor respirator cartridges

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ABSTRACT

A passive visual end of service life indicator (ESLI) for certain organic vapors has been attached to the inside wall of an organic vapor respirator cartridge. The opposite side of the ESLI touches activated carbon inside the cartridge. During use, organic vapors moving through the cartridge adsorb into both the carbon and the ESLI. The cartridge body is clear so that when vapor concentrations meet a certain threshold, the user may observe the progressive development of an indicator bar down the side of the ESLI. The cartridge is deemed ready to change when any part of the indicator bar touches a marked end line. The performance of the ESLI was observed when the cartridge was tested against a variety of organic vapors, exposure concentrations above the minimum indication level, humidities, temperatures, flow rates, and mixtures. In all cases, the ESLI indicated end of service life with more than 10% cartridge service life remaining (which is a NIOSH test criteria). The results were also compared to mathematical predictions of cartridge service life.

KEYWORDS

Cartridge; ESLI; indicator; organic vapor; respirator; service life

Introduction

Users of gas/vapor respirators often ask how frequently they should replace their cartridges. In some countries, users rely on taste, smell, or irritation of gases or vapors coming through the cartridge. However, some contaminants do not have strong warning properties, and sensory perception varies greatly between individuals. Additionally, workers who have been exposed to certain chemicals for a long time may have a reduced olfactory sensitivity to those particular chemicals. Moreover, employers in the United States and certain other countries are required to develop a cartridge change schedule based either on empirical data or an end of service life indicator (ESLI).^[1] However, ESLIs have been only been available for a few specific respirator cartridges. Favas discussed that although patents exist all the way back to 1925, there have been many drawbacks related to shelf life, visibility, ease of use, and limitations in the range of detection.^[2] An ESLI roundtable discussion held at the 2012 International Society for Respiratory Protection Conference included

presentations on the history of ESLI development as well as challenges related to implementation and adoption.^[3]

An optical sensor specifically designed for organic vapors was described in detail by Rakow et al.^[4] and Thomas et al.^[5] In short, this organic vapor sensor consists of a polymer of intrinsic microporosity (PIM) that adsorbs organic vapors in a manner similar to the activated carbon that is used in respirator cartridges. The PIM is located between a partially reflective layer and a permeable reflective layer, as shown in Figure 1. Incident light enters the top of the sensor. A partial mirror reflects some light (1) while allowing the remaining light (2) to travel through the porous membrane, reflect off of the back of the sensor, return through the porous membrane, and pass through the partial mirror at the front of the sensor. Light from (1) and (2) may combine through constructive interference and is observed as a color. Organic vapors adsorbed into the PIM can change the PIM's index of refraction and thickness. This may cause a color shift relative to the background; from green to red, or red to

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Figure 1. Sensor cross-section and constructive interference.

green, depending on the viewing angle. An unchanged background is maintained by incorporating masked areas into the sensor design.^[6]

The wavelength shift between the indicator bar and the background is measured in nanometers. As more vapor is adsorbed into the membrane, the color shift becomes larger (more intense). However, the vapor concentration that causes a noticeable shift in color, the minimum indication level (MIL), is different for each organic vapor. Through an internal 3M human factors study it was previously determined that 99% of test subjects could detect a 10 nm wavelength shift in this ESLI under low light conditions. To determine the MIL for an individual compound, the organic vapor was adsorbed onto the sensor material at different concentration levels and the wavelength shift was measured. Allowing for a safety factor, the organic vapor concentration (ppm) that caused a 15 nm wavelength shift was recorded as the MIL. MILs for some of the organic vapors used in this study are given in Table 1.

The focus of the current study was to attach this optical sensor (approximately 1 cm × 1 cm) to the inside wall of an organic vapor respirator cartridge, next to the activated carbon, and test its performance as an ESLI—that is, indicating cartridge change prior to organic vapor breakthrough. The cartridge body is clear so that incident light may enter the ESLI sensor, and reflected light may be viewed by the user. As organic vapors move through the cartridge, they also pass through the permeable reflective layer and adsorb into the PIM. This may cause a color shift as described above. If the exposure concentration is

greater than the MIL, the progression of organic vapors through the cartridge may be seen via growth of the ESLI indicator bar as illustrated in Figure 2. Unlike many other ESLIs, the color change of the indicator bar is not compared to an “end-state” reference color. Rather, the cartridge must be changed when any part of the indicator bar touches the marked end line.

Most global respirator certification standards do not have test requirements for ESLI’s. However, the US National Institute for Occupational Safety and Health (NIOSH) gives requirements for a vinyl chloride ESLI.^[7] NIOSH also provides general ESLI requirements for visibility, drop test, and performance in their standard testing procedures and requires that cartridge end of life is indicated at or before 90% of the actual service life.^[8-10]

The purpose of this study was to validate the safety performance of the ESLI relative to cartridge service life for various organic vapors, exposure levels above the MIL, constant and variable airflow, temperature, humidity, water vapor preconditioning, and organic vapors mixtures because they all may impact organic vapor cartridge service life. The ESLI end line was positioned at a specific height on the side of the cartridge with the goal of having at least 10% service life remaining for all of our test conditions, even after considering manufacturing variability. Potential sources of manufacturing variability may include the physical properties of the activated carbon (particle size distribution, apparent density, moisture, micropore volume, etc.); carbon fill weight and level (both of which can affect flow patterns within the cartridge); and weld of the cartridge lid.

The performance of the ESLI was also compared to a mathematical model used to predict organic vapor service life.^[11] Where applicable, the “predicted” service life was adjusted for both relative humidity and mixtures. Correction factors for high relative humidity were based on previous testing done at 65, 75, 85, and 90% RH.^[12,13] Service life for mixtures was estimated based on OSHA guidance for its compliance officers.^[14]

However, it is important to note that the ESLI and the mathematical model are not directly comparable. The math model predicts time until the amount of vapors

Table 1. Minimum Indication Limit (MIL).

Organic Vapor	MIL (ppm)
Acetone	1400
sec-Butanol	83
n-Butyl acetate	2
Heptane	12
Methyl ethyl ketone	175
Methyl isobutyl ketone	5
Tetrachloroethylene	20
Trichloroethylene	66
Toluene	8
Xylene	2

Figure 2. Progression of the ESLI Indicator Bar.

coming through the cartridge has already reached a pre-determined level. In contrast, the ESLI is designed to show an end point with at least 10% service life remaining according to the NIOSH test criteria. In addition, the math model used does not include options for cyclical breathing or cartridge pre-humidification.

Method

As shown in [Figure 3](#), testing was done in an apparatus similar to the system described in the NIOSH test method for determining organic vapor cartridge service life.^[15] An organic liquid was delivered by a syringe pump and evaporated into a humidified airstream. Unless otherwise noted, the volumetric flow rate of the constant flow airstream containing the organic vapor was 32 L/min $\pm$ 0.5 L/min per cartridge (representing 64 L/min for a dual cartridge respirator). The flow was measured using a Linear OEM Mass Flowmeter (4000 series, TSI, Shoreview, MN) and verified using a soap bubble flow meter (GF-1500, Gilmont, Barrington, IL). Unless noted, the humidity was controlled at 50% RH $\pm$ 2% by a Chilled Mirror Hygrometer (Edgetech Dewmaster, Marlborough, MA). Unless noted, cartridges were not preconditioned prior to testing. Unless noted, temperature was measured but not controlled. For room temperature tests, the average temperature was approximately 23°C. Atmospheric pressure in St. Paul, MN is nominally 0.97 atmospheres. The well-mixed airstream containing the organic vapor was then presented to the ESLI cartridge in a clear acrylic chamber to allow for viewing of the ESLI.

End of service life was recorded two separate ways. The first method used a camera on the outside of the chamber

that took pictures of the sensor at timed intervals during the test. Upon completion of the test, the pictures were evaluated to determine when any part of the indicator bar touched the end of service line marked on the side of the cartridge.

In addition to the camera, the effluent stream was measured by the appropriate analyzer: total hydrocarbon analyzer (23-550, GOWMAC, Bethlehem, PA), or GC-FID (8610C, SRI-GC, Torrance, CA). Cartridge service life was recorded as the time for the vapor concentration exiting the cartridge to reach one half of the occupational exposure limit (OEL) for the specific organic vapor. This end-point was chosen because cartridges must be changed before hazardous levels exit the cartridge, and 50% breakthrough is a common option in service life software programs. After 10% more time beyond the ESLI end point, the organic vapor concentration exiting the cartridge was also recorded.

To evaluate the effectiveness of the indicator under various conditions, the following tests were completed.

High and low concentration of six representative organic vapors

Six organic vapors were chosen to demonstrate the breadth of performance of the sensor. The compounds were chosen based on their prevalence in workplace environments and as representative of different classes of organic vapors. These included heptane (alkane), methyl isobutyl ketone (ketone), toluene (aromatic), tetrachloroethylene (halogenated alkane), n-butyl acetate (ester), and sec-butanol (alcohol). Each of these organic vapors was tested at low and high concentrations. The low

Figure 3. Experimental setup.

inlet concentration was chosen as the OEL. The high concentration was chosen as the lowest of three values: 50X times the OEL, the NIOSH 1990 immediately dangerous to life or health (IDLH) limit, or 10% of the lower explosive limit (LEL). The first two criteria for the high concentration mimic the maximum use concentration allowed by US OSHA for full facepiece respirators,^[1] and the third was for safety in our laboratory. All concentrations were above the MIL for each organic vapor. Cartridges were not preconditioned prior to testing.

High and low humidity

Previous work had shown that the ESLI sensor by itself (outside of a cartridge) showed a small wavelength shift at high relative humidity.^[5] When the sensor is placed inside a cartridge next to activated carbon, it is expected that the carbon will preferentially adsorb water in competition with the ESLI, and thus water vapor should not interfere with the ESLI. Three organic vapors were chosen to demonstrate performance at high and low humidities. Heptane and toluene were chosen because they represent non-polar species, and have a different affinity for adsorbing into carbon and the ESLI. Methyl ethyl ketone (MEK) represents an organic vapor that is soluble in water. Testing was over the range of 25–70% RH for heptane and toluene, and 25–85% RH for MEK.

Pre-humidified cartridges were also tested against heptane, MEK, and toluene. Pre-humidification was done by exposing the cartridges to 85% RH for 6 hours at 25 L/min. After exposure, cartridges gained approximately 19.5 grams of water. Cartridges were placed in a metalized bag to prevent moisture from escaping, and stored at room temperature. Cartridges were then challenged with the organic vapor within 24 hr after pre-humidification. Testing after pre-humidification was done at 50% RH and at 70% RH.

High and low temperature

Two representative organic vapors (MEK and toluene) were chosen to demonstrate performance of the sensor in the cartridge at high and low temperatures. MEK was chosen because it causes a smaller wavelength shift in the indicator than some other organic vapors at the same concentration. Toluene was chosen because it is a common organic vapor.

To control temperature, the contaminated airstream was passed through a heat exchanger filled with a 50/50 mix of ethylene glycol and water. The cartridge was placed very close to the exit of the heat exchanger to ensure

that the airstream did not gain or lose heat. Thermocouples were placed inside the air line before the cartridge, after the cartridge, and inside the heat exchanger to ensure that the temperature was controlled properly. Three temperatures were evaluated: cold (0–5°C), room temperature (20–25°C), and hot (30–35°C). These temperatures were chosen as reasonable for most workplaces. Humidity was controlled prior to heating the contaminated airstream and set so that the measured relative humidity was approximately 50% at the cartridge.

Breathing machine (variable flow test)

Tests were run using a breathing machine (B8501, Warwick Technology Limited, Warwick, United Kingdom) to simulate a person breathing. Cyclic sinusoidal breathing rates of 20 LPM and 32 LPM on single cartridges were chosen to mimic “standard” and “heavy” breathing rates of 40 and 64 LPM, respectively, on an assembled dual cartridge respirator. Breathing rate was held constant at 30 breaths per minute. Heptane was tested at either 1000 ppm (for the “heavy” breathing rate) or 165 ppm (for the “standard” breathing rate). Tests were done at both 50% and 85% RH.

Organic vapors mixtures

Organic vapors in a mixture will adsorb into the ESLI together to increase the likelihood of a visible change of the indicator bar. Tests were run in a similar manner described by Wood to determine how the sensor would respond to organic vapor mixtures.^[16] Mixtures consisting of two or three of the following organics were evaluated: acetone, cyclohexane, MEK, methyl isobutyl ketone, trichloroethylene, toluene, or xylenes. Testing was done at 100–350 ppm, 36.2 liters per minute (corresponding to 72.4 liters per minute on an assembled dual cartridge respirator), and relative humidity was controlled at 25%, 50%, or 75% RH.

Results

Per our goal of evaluating the safety performance of the ESLI, Tables 2–7 show time for the ESLI indicator to reach the marked end line, mathematically predicted service life until the indicated breakthrough concentration, and measured service life until the indicated breakthrough concentration. The breakthrough concentration was defined as one half of the OEL for each organic vapor. In most cases, tests were repeated four times to help understand variability in both the ESLI and cartridge service life. When reported, the “±” after the time is the standard deviation of the four trials. When tests were done less than

Table 2. ESLI and service life for six organic vapors.

Vapor	Inlet Concentration (ppm)	Breakthrough Concentration (ppm)	ESLI (min)	Predicted Service Life (min)	Measured Service Life (min)
Heptane	85	42.5	628 ± 47	1090	1271 ± 12
	1000		64 ± 7	109	111 ± 4
Methyl isobutyl ketone	20	10	2295 ± 148	4298	5303 ± 58
	1200		51 ± 10	102	99 ± 1
Toluene	20	10	1765 ± 77	4906	5197 ± 97
	1000		67 ± 13	141	140 ± 3
Tetrachloroethylene	25	12.5	1935 ± 160	4476	4986 ± 339
	500		106 ± 14	294	277 ± 2
n-Butyl acetate	150	75	308 ± 33	828	869 ± 10
	1700		28 ± 8	79	75 ± 2
sec-Butanol	100	50	650 ± 137	1172	1398 ± 6
	1700		38 ± 5	95	90 ± 2

four times, no standard deviation is reported. In the case of the mixture testing, a single datum was collected for each condition.

Table 2 includes results from six types of organic vapors tested at 50% RH under low and high organic vapor concentrations. All concentrations (low and high) were above the MIL. The ESLI indicator bar reached the end line and indicated time to change the cartridge well before the exit concentration reached $\frac{1}{2}$ OEL. After 10% more time beyond the ESLI end point, there was essentially no detectable organic vapor in the effluent stream. The predicted service life was similar to the measured service life under these conditions.

The high vapor concentrations evaluated in this study are thought to be rare in most workplaces. During high concentration experiments, the wave of organic vapor moving through the cartridge was reflected by an indicator bar with a jagged leading edge. The time for the ESLI was recorded when any part of the indicator bar reached the end-of-service line. The jagged leading edge results

from high organic vapor concentrations being in dynamic adsorption equilibrium between the activated carbon bed and the ESLI, while at the same time moving around the carbon granules at high flow rates. The cartridge may be adjusted to a different viewing angle to clearly see progression of the indicator bar. (In a separate internal 3M human factors study, subjects viewing the cartridge by itself oriented the cartridge slightly without coaching to view the ESLI.)

The effects of moisture are shown in Tables 3, 4A, and 4B. Table 3 includes cartridges that have not been preconditioned, but moisture is simultaneously competing with the organic vapor for active adsorption sites. Tables 4A and 4B include data for cartridges that have been preconditioned with water vapor and then tested at either 50% or 70% RH. The mathematical model used to predict service life does not include pre-humidification, so predicted service life in Tables 4A and 4B is the same as what is shown in Table 3 or is listed as not applicable (NA).

Table 3. ESLI and service life at different relative humidities.

Vapor	Inlet Concentration (ppm)	Breakthrough Concentration (ppm)	RH (%)	ESLI (min)	Predicted Service Life (min)	Measured Service life (min)
Heptane	85	42.5	25	616 ± 71	1090	1291 ± 3
			50	628 ± 47	1090	1271 ± 12
			70	433 ± 76	670	1216 ± 7.5
	1000		25	48 ± 4	109	109 ± 1
			50	64 ± 7	109	111 ± 4
			70	58 ± 5	91	104 ± 3
Toluene	20	10	25	1960	4906	5293
			50	1765 ± 77	4906	5197 ± 97
			70	1580	2213	4551
	1000		25	60	141	139
			50	67 ± 13	141	140 ± 3
			70	57	119	134
MEK	200	100	25	250	405	544
			50	210 ± 42	405	558 ± 10
			70	175	118	464
	1400		85	150 ± 12	64	349 ± 13
			25	47	86	105
			50	43 ± 5	86	105 ± 2
			70	45	48	99
			85	31 ± 12	36	91 ± 1

Table 4A. ESLI and service life, with and without pre-humidification. Testing done at 50% RH.

Vapor	Inlet Concentration (ppm)	Breakthrough Concentration (ppm)	Pre-humidified	ESLI (min)	Predicted Service Life (min)	Measured Service life (min)
Heptane	85	42.5	Yes	575 ± 65	NA	1252 ± 14
			No	628 ± 47	1090	1271 ± 12
	1000		Yes	42 ± 8	NA	87 ± 1
			No	64 ± 7	109	111 ± 4
Toluene	20	10	Yes	1805 ± 173	NA	5263 ± 131
			No	1765 ± 77	4906	5197 ± 97
	1000		Yes	28 ± 3	NA	104 ± 1
			No	67 ± 13	141	140 ± 3
MEK	200	100	Yes	210 ± 43	NA	587 ± 6
			No	210 ± 42	405	558 ± 10
	1400		Yes	21 ± 6	NA	79 ± 1
			No	43 ± 5	86	105 ± 2

As expected, measured, predicted, and ESLI service lives were shorter at high relative humidity, especially for lower vapor concentrations. This reduction in service life is because water vapor may take up pore space normally used to adsorb organic vapors. Thus, the organic vapor wave front goes through the cartridge more rapidly. Preconditioning the cartridge reduced the measured and ESLI service life for high concentration tests but had very little impact on low concentration tests. This suggests that the duration of the low concentration tests was long enough for the water to be driven off, thus creating adsorption sites for the organic vapors.

The ESLI indicator bar reached the end line well before the exit concentration reached $\frac{1}{2}$ OEL. In all the tests except one, when the ESLI indicator bar reached the end line plus 10% more time, the exit concentration of the organic vapor was below the analytical detection limits. In one of the 1000 ppm toluene, 25% RH tests, 1 ppm of toluene was observed, but this is less than the $\frac{1}{2}$ OEL for toluene (10 ppm); thus the sensor still appropriately indicated a safe time to change the cartridge.

The predicted service life was close to the measured service life for the 25% and 50% RH conditions, particularly at the higher concentrations, but underestimates service life for the 70% RH tests, especially at the lower exposure concentrations. For higher concentrations of MEK at

70% and 85% RH, the predicted service life was similar to the time until the ESLI end point.

The effect of temperature on service life and the ESLI is shown in Table 5. As expected, service life decreased with higher temperature. (At higher temperature, organic vapors are less likely to adsorb into the carbon pores or the ESLI.) The ESLI indicator bar reached the end line well before the exit concentration reached $\frac{1}{2}$ OEL. In all cases, there was no observed organic vapor in the effluent stream at 10% beyond the time the ESLI indicator bar reached the marked end line. In addition, the intensity of the indicator bar was carefully observed in the high temperature tests. MEK gives a less intense color change than some of the other organic vapors tested, but the indicator bar was still clearly visible, even during the low concentration test. The predicted service life was reasonably similar to the measured service life, although less so for the 200 ppm MEK.

The effect of cyclic flow versus constant flow on service life and the ESLI is shown in Table 6. There was little perceptible difference in the service life observed via the ESLI. Measured service life was similar for both flow patterns under low humidity conditions; however, the measured service life decreased substantially for the combination of high humidity and lower concentration of heptane. More investigation is needed to determine if this

Table 4B. ESLI and service life, with and without pre-humidification. Testing Done at 70% RH.

Vapor	Inlet Concentration (ppm)	Breakthrough Concentration (ppm)	Pre-humidified	ESLI (min)	Predicted Service Life (min)	Measured Service life (min)
Heptane	85	42.5	No	434 ± 76	670	1216 ± 8
			Yes	505 ± 73	NA	1200 ± 23
	1000		No	58 ± 5	91	104 ± 3
			Yes	44 ± 16	NA	81 ± 1
Toluene	20	10	No	1580	2213	4550
			Yes	1150	NA	4031
	1000		No	57	119	134
			Yes	35 ± 7	NA	101 ± 5
MEK	200	100	No	175	118	464
			Yes	120 ± 37	NA	475 ± 19
	1400		No	44 ± 5	48	98 ± 4
			Yes	20	NA	64

Table 5. ESLI and service life at different temperatures.

Vapor	Inlet Concentration (ppm)	Breakthrough Concentration (ppm)	Temperature (°C)	ESLI (min)	Predicted Service Life (min)	Measured Service life (min)
Toluene	1000	10	0–5	85 ± 9	145	147 ± 3
			20–25	66	141	139
			30–35	48 ± 14	137	127 ± 7
MEK	200	100	0–5	297 ± 59	574	732 ± 109
			20–25	215 ± 35	405	556 ± 8
			30–35	160 ± 18	332	426 ± 15
	1400		0–5	51 ± 9	104	115 ± 8
			20–25	41 ± 1	86	103 ± 2
			30–35	37 ± 2	77	93 ± 3

observation would be similar for other organic vapors and test conditions, but is beyond the scope of this article.

In these tests the ESLI indicator bar still reached the end line well before the exit concentration reached $\frac{1}{2}$ OEL. In all cases, there was no observed organic vapor in the effluent stream at 10% beyond the time the ESLI indicator bar reached the marked end line. The mathematical model used to predict service life does not include the option for cyclic flow, and thus comparison was not possible.

The effect of certain organic vapor mixtures on service life and the ESLI is shown in Table 7. For each mixture, the data for the ESLI, predicted service life and measured service life are for the organic vapor noted as exiting the cartridge first. In these tests the ESLI indicator bar still reached the end line well before the exit concentration reached $\frac{1}{2}$ OEL. In all cases, there was no observed organic vapor in the effluent stream at 10% beyond the time the ESLI indicator bar reached the marked end line. The mathematically predicted service life was less than the measured service life. For some of the 75% RH tests, the predicted service life was even less than the time until the ESLI end point. This suggests that in some cases, the correction factors used to help predict service life at elevated relative humidity may be too high.

An example of the exit concentration from testing against 350 ppm acetone, trichloroethylene, and xylene at 50% RH is shown in Figure 4. Both acetone and trichloroethylene had significant roll-up occur during this test: the effluent concentration of both organic vapors temporarily exceeded the inlet concentration by almost a

factor of two. When roll-up occurs inside the cartridge, the service life can be significantly shortened. However, this roll-up phenomenon did not interfere with the performance of the ESLI.

Discussion

The ESLI end line was positioned to have at least 10% remaining service life (similar to the NIOSH testing requirements) for all test conditions in this study, even after considering manufacturing variability. Pooling the data across all challenges ($n = 257$), the average ratio of the time for the ESLI indicator bar to reach the marked end line to the measured cartridge service life is 0.46 with a standard deviation of 0.1 and a maximum ratio of 0.75. We tested the assumption of normality for the ratio data using the Anderson-Darling test and found no significant evidence of non-normality ($p = 0.168$). Based on this distribution, we would expect that 99.73% of all ratios would fall between ± 3 standard deviations which places the upper limit at approximately 0.76. According to these data, workers using the ESLI in accordance with the product user instructions would be changing cartridges prior to 10% of the remaining service life as required by NIOSH. More investigation would be needed to make statistically valid conclusions about how each individual test condition affects the ESLI.

The performance of this ESLI was also compared to software programs developed by respirator manufacturers and other organizations to estimate respirator cartridge service life. Even for the simpler case of a single organic

Table 6. Effect of cyclic vs. constant flow on ESLI and service life.

Vapor	Inlet Concentration (ppm)	Breakthrough Concentration (ppm)	RH (%)	Flow Rate (L/min)	Flow Type	ESLI (min)	Predicted Service Life (min)	Measured Service life (min)
Heptane	165	42.5	50	20	Cyclic	440	NA	927
					Constant	440	946	1005
			85		Cyclic	250	NA	616
					Constant	270	533	806
	1000		50	32	Cyclic	43	NA	98
					Constant	47	109	102
			85		Cyclic	52	NA	91
					Constant	46	85	93

Table 7. ESLI and service life for organic vapor mixture.

Vapor Mixture	Inlet Concentration (ppm)	Breakthrough Concentration (ppm)	First OV Observed	RH (%)	ESLI (min)	Predicted Service Life for first observed OV (min)	Measured Service life for first observed OV (min)
MEK	200	100	MEK	25	78	152	212
Toluene	200	10		50	101	152	209
Xylene	200	50		75	84	54	174
MEK	200	100	MEK	50	220	262	490
Xylene	100	50		75	110	69	254
Cyclohexane	300	50	Cyclohexane				
Methyl isobutyl ketone	300	10		50	92	117	127
Toluene	300	10		75	63	69	110
Acetone	350	250	Acetone				
Trichloroethylene	350	10		50	32	62	101
Xylene	350	50		75	31	10	98

vapor at low relative humidity, accuracy of a mathematical model to predict service life may vary by $\pm 50\%$.^[11] The accuracy of the math model used in this study was improved by using empirically derived constants for a similar organic vapor cartridge instead of using “universal” constants for organic vapor cartridges. However, the math model still underestimated service life for high relative humidity. This may be because the correction factors were based on testing with water immiscible (insoluble) organic vapors to demonstrate worst-case effects. The mathematical model also underestimated service life for mixtures. Some disagree with the underlying assumptions of the OSHA method for estimating service life for mixtures, and have commented that it should only be considered as a “rule of thumb.”^[17] Subsequent models have been developed to predict the effects of humidity, mixtures, and migration of organic vapors through the respirator cartridge during storage.^[16,19,20] Yet, these mathematical models still both under and overestimate service life.

At a more basic level, software programs are also limited by the accuracy of the data entered. Air monitoring data is unfortunately often lacking, especially in emerging markets. Even if air sampling has been done, it may not account for the large variability of individual worker exposure levels within a workplace.^[18] Mathematical models also do not take into account changes in exposure, breathing rates, environmental conditions, and storage conditions during nonuse, each of which impact cartridge service life. One of the great advantages of an ESLI is that the performance is based on actual conditions of use, storage and reuse.

Conclusion

An end of service life indicator (ESLI) may be used to determine when to change respirator cartridges. NIOSH requires that end of cartridge life is indicated at or before 90% of the actual service life. The optically based ESLI in an organic vapor cartridge described in this paper was tested against a variety of organic vapors, exposure concentrations above the MIL, humidities, temperatures, flow rates, and a few sample organic vapor mixtures. At 10% beyond the time when the ESLI indicator bar reached the marked end line, the measured organic vapor in the effluent stream was below 50% of the occupational exposure limit, and in almost every case there was no measured amount of organic vapor. The average ratio of the time for the ESLI indicator bar to reach the marked end line to the measured cartridge service life was 0.46 with a standard deviation of 0.1 and a maximum ratio of 0.75. Mathematical models used to predict cartridge service life are also helpful, but have their own limitations and are not necessarily superior to the ESLI. This ESLI can provide real-time feedback according to changes in contaminants, exposure concentrations, temperature, humidity, and breathing rates. Future studies may evaluate this ESLI cartridge in the workplace.

Figure 4. Rollup in a mixture of 350 ppm each of acetone, trichloroethylene, and xylene at 50% RH.

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